

Scintillators and Imaging in EUV/XR Spectral region

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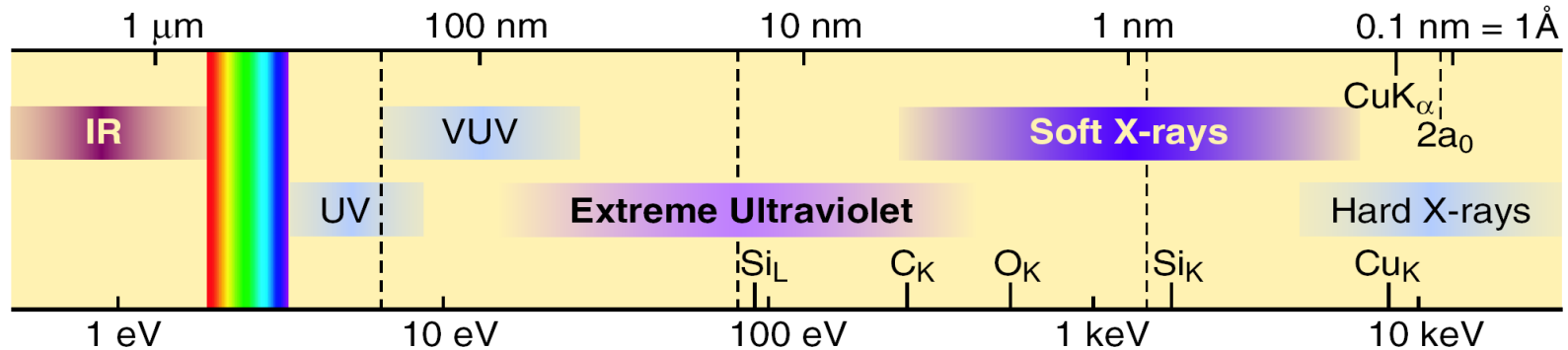
Outline

- **Motivation**
- **EUV/BEUV/SXR/XR Imaging Detectors**
- **Monocrystal Scintillators**
- **Quantum efficiency**
- **Selected applications**

Motivation

- **Collector optics for EUV/SXR lithography**
- **Experimental tools for EUV/SXR lithography**
- **Diagnostic tools for EUV/SXR lithography**
- **Novel optical systems for EUV/SXR lithography**
- **Novel optical systems for EUV/SXR/XR microscopy**
- **Novel optical systems for EUV/SXR/XR tomography**

Electromagnetic radiation spectrum



D. T. Attwood *Soft X-rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge University Press, Cambridge, 1999)

13.5 nm – 92 eV

EUV Lithography

6.2 nm – 200 eV

BEUV Lithography

2.34 – 4.39 nm – 283 - 531 eV

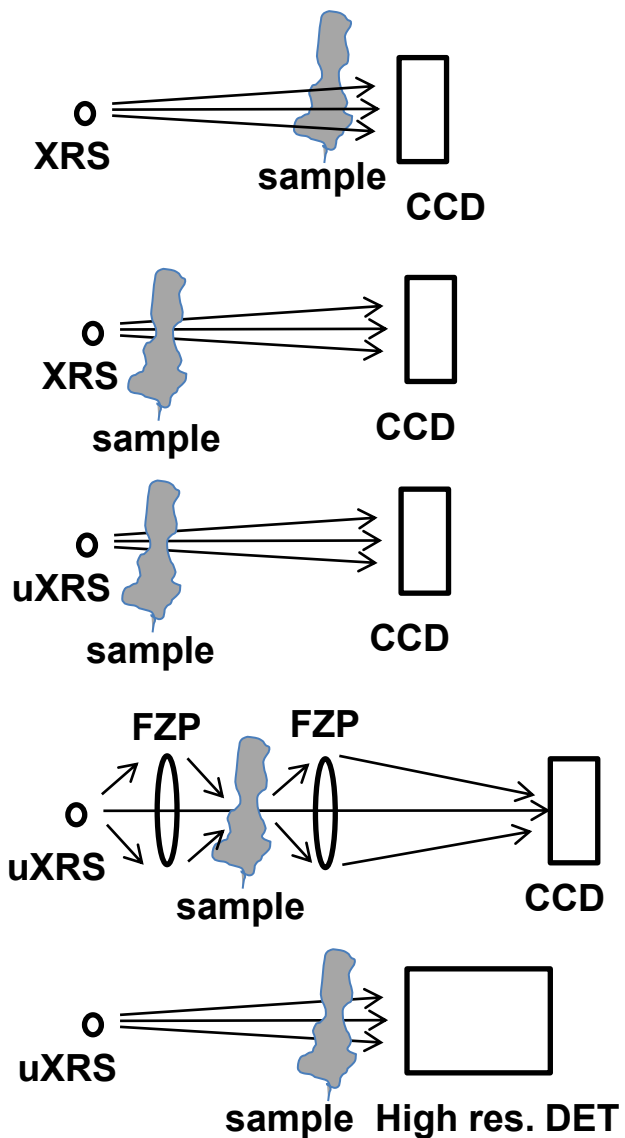
Water Window Microscopy

Imaging in EUV and X-ray region plays important role in radiography, tomography, spectroscopy and lithography.

Direct detection with use of CCD back illuminated detectors features high sensitivity and relatively low optical resolution given by minimum available pixel size.

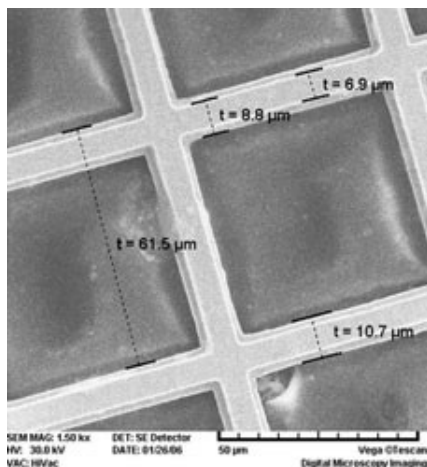
Detection using powder scintillators placed as a thin layer on fibre optic plate or directly on CCD sensor has still relatively high sensitivity and low resolution.

Monocrystal scintillators have advantage of continuous homogeneous structure resulting in high resolution. However, they usually require an additional magnifying optical system in front of CCD detector. Overall sensitivity is relatively low due to scintillator quantum efficiency and throughput of the optical system.

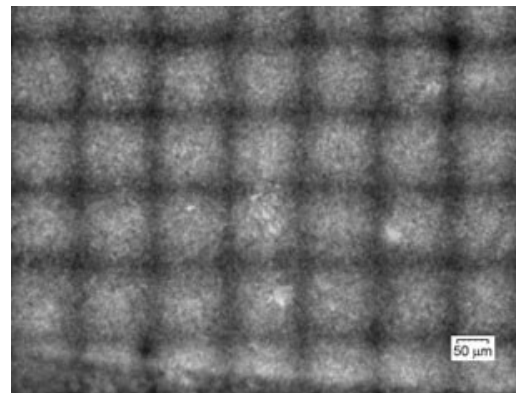


EUV/XR IMAGING					
Source size/W	Optics	Pixel size	Resolution	Signal	Cost
L/H	N	L	L	H	L
L/H	N	L	L	H	L
VS/low	N	L	H	L	H
S/low	Y	L	VH	VL	VH
M/H	N	S	H	H	H

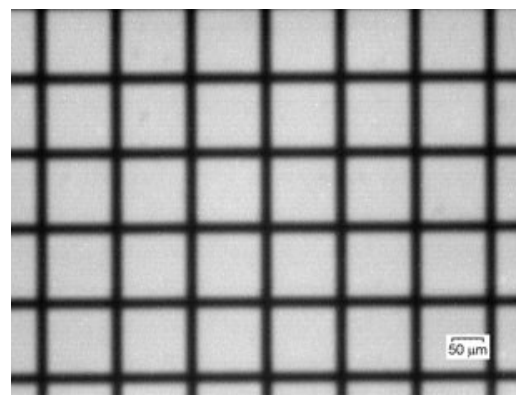
Powder scintillator and monocrystal scintillator comparison



Sample: The gold mesh image (SEM)



**The gold mesh X-ray image
(P43 phosphor screen)**



**The gold mesh X-ray image
(YAG:Ce scintillator screen)**

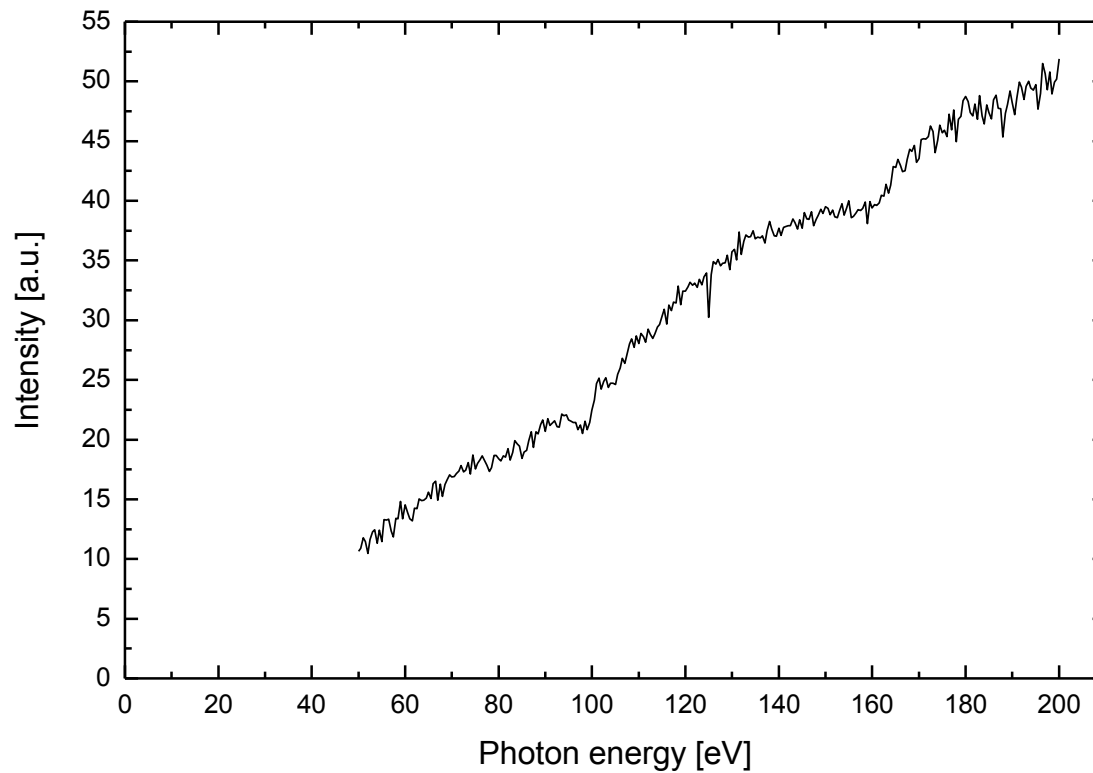
CRYTUR SCINTILLATORS

www.crytur.com

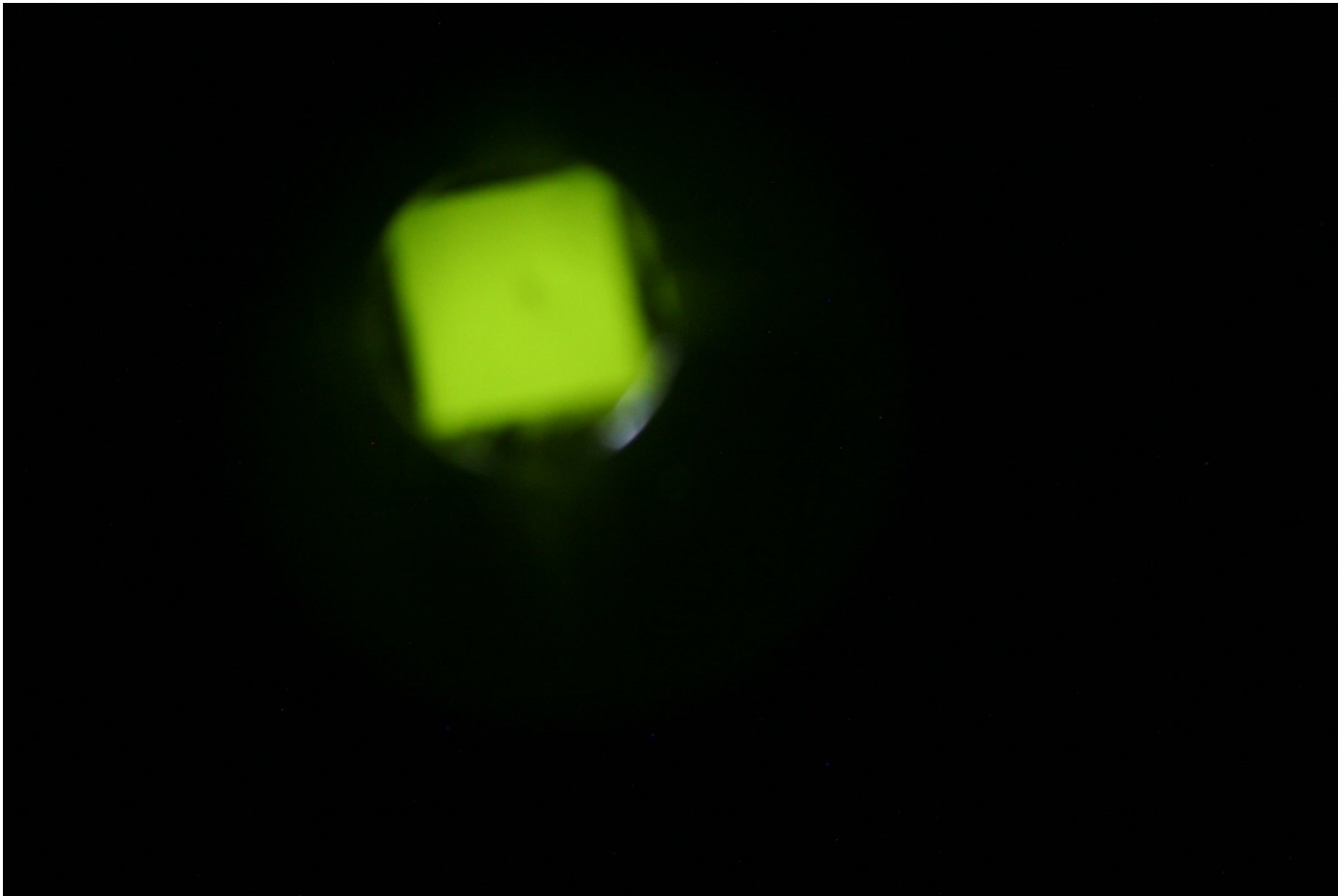
Table of physical parameters

	NaI:Tl	BGO	YAG:Ce	YAP:Ce	CRY-019	CSI:Tl	CRY-018
Density [g/cm ³]	3.67	7.13	4.55	5.37	7.4	4.51	4.50
Hardness [Mho]	2	5	8.5	8.6	5.8	2	5.8
Index of refraction	1.85	2.15	1.82	1.95	1.82	1.78	1.79
Crystal structure	cubic	cubic	cubic	rhombic	monoclinic	cubic	monoclinic
Hygroscopic	yes	no	no	no	no	no	no
Cleavage	yes	no	no	no	yes	Slightly	yes
Light output [% NaI:Tl]	100	15 - 20	40	60	40 - 75	45	80
Emmision [nm]	415	480	550	370	415 - 420	550	425
Decay Time [ns]	230	300	70	25	46	900	45
Energy Resolution [% at 661 keV]	7.2	12	7.2	6.7	8.5	8.5	7
Radiation length x_0 [cm]	2.9	1.1	3.5	2.7	1.2	1.86	2.74
Photon yield @300K [10 ³ Ph/MeV]	38	8 - 10	35	25	28	52	32

LuAG:Ce 8109. Excitation for 520 nm emission. 11 K.



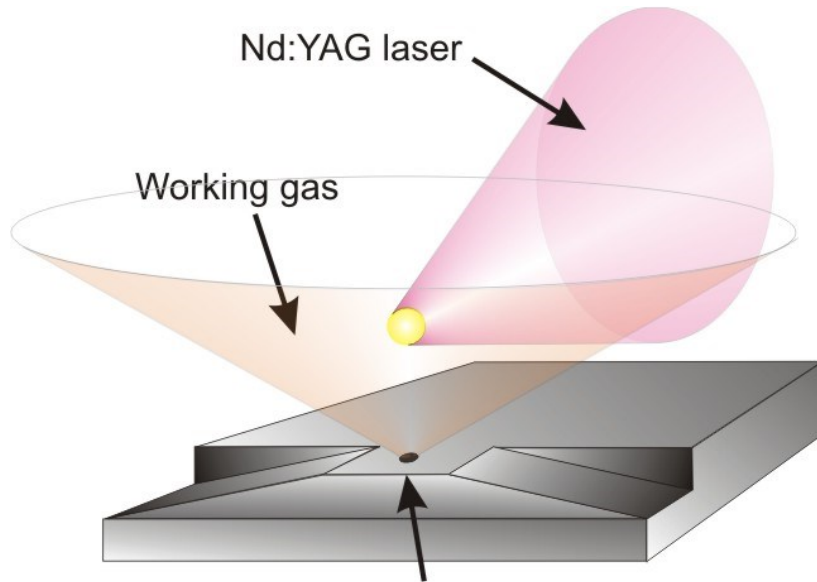
Ce:YAG crystal, CAS Prague, CRYTUR



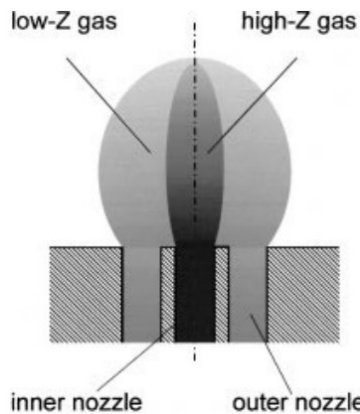
Ce:YAG crystal fluorescence
(EUV from LPP Argon gas-puff source, 550 nm visible light)
WAT, Warsaw

LPP - Double stream gas puff target

Single stream gas puff target

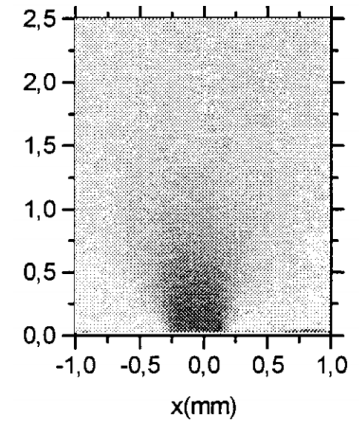


Single nozzle



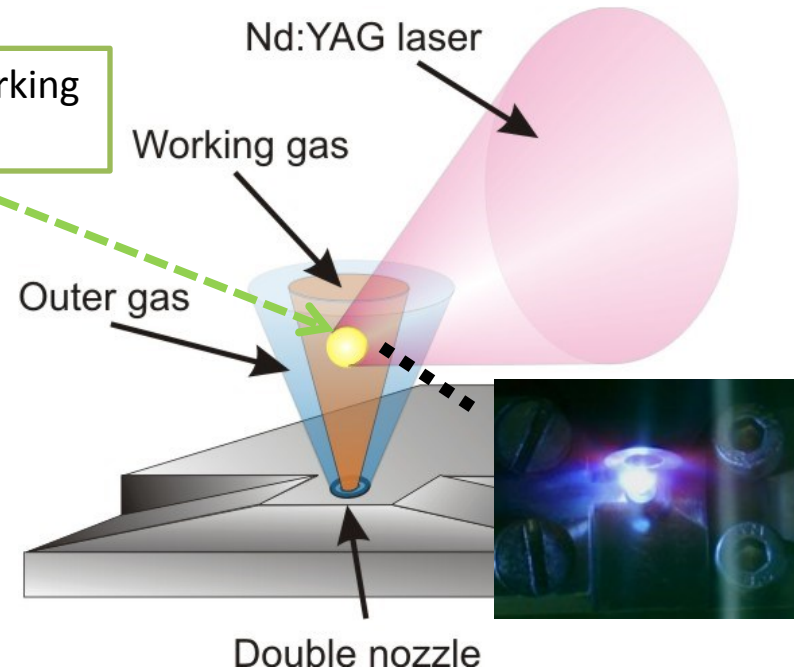
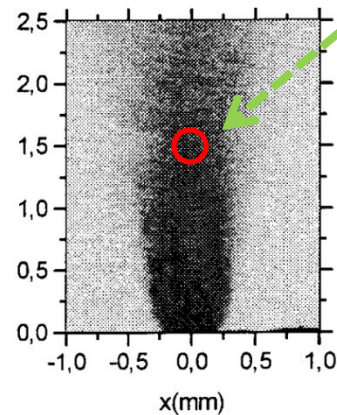
Problems:

- ✓ high working gas jet divergence
- ✓ difficult to achieve a proper gas density far away from the nozzle
- ✓ nozzle ablation and debris production



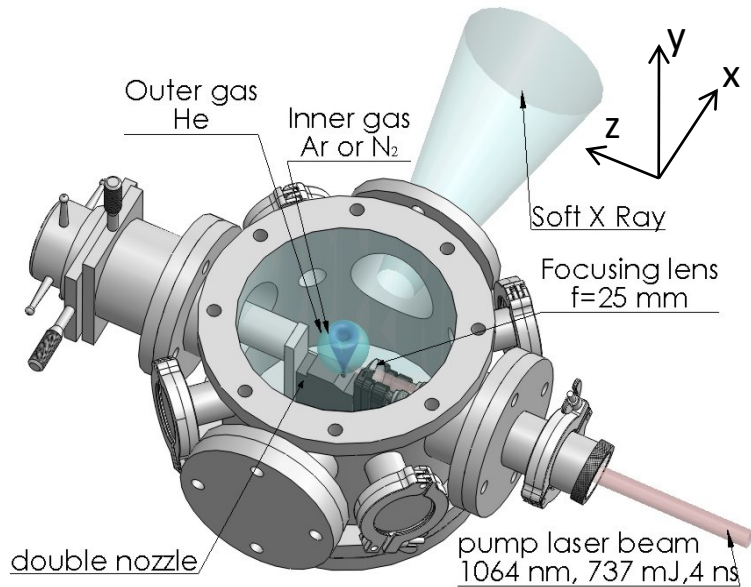
Double stream gas puff target

Optimal working gas density



Double nozzle

LPP - Gas puff target EUV laser-plasma short wavelength source



Scheme of the gas-puff target source



Photograph of the setup

Pumping laser	Nd:YAG laser (EKSPLA), 4 ns/500mJ pulses, repetition rate 10Hz
Nozzle	Inner: circular 0.4mm in diameter Outer: ring 0.7mm/1.5mm diameters
Gasses	Working gasses: Ar, Kr, Xe, O₂, N₂ , outer gas : He

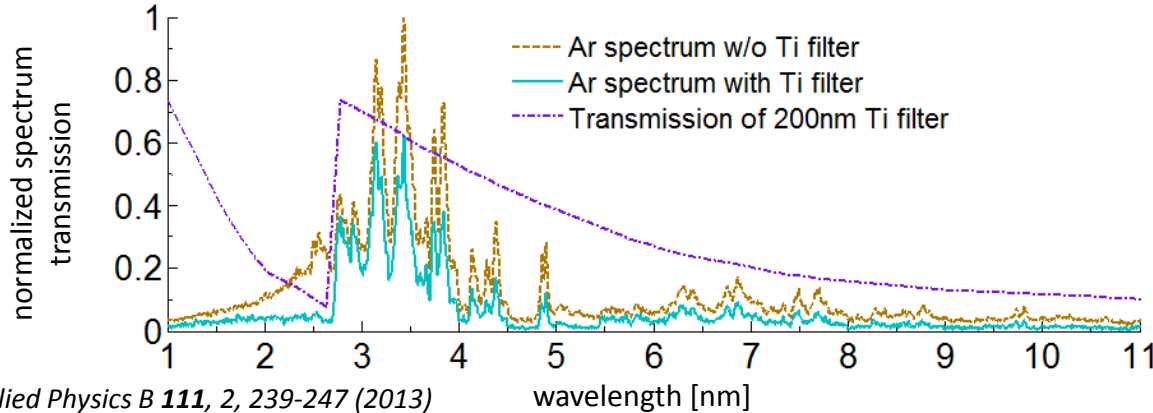
Advantages:

- ✓ no debris from gaseous targets
- ✓ compact construction, high repeatability
- ✓ high conversion efficiency, very robust – thousands of shots/day

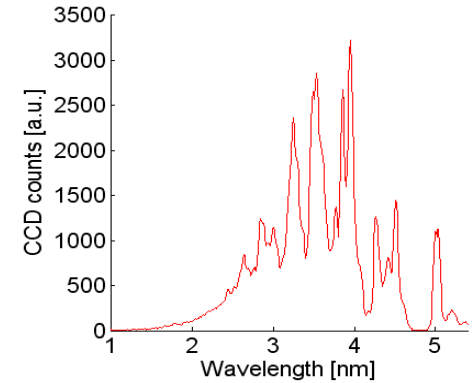
54
Xe
131.29

SXR SPECTRA

Argon emission on the „water window“

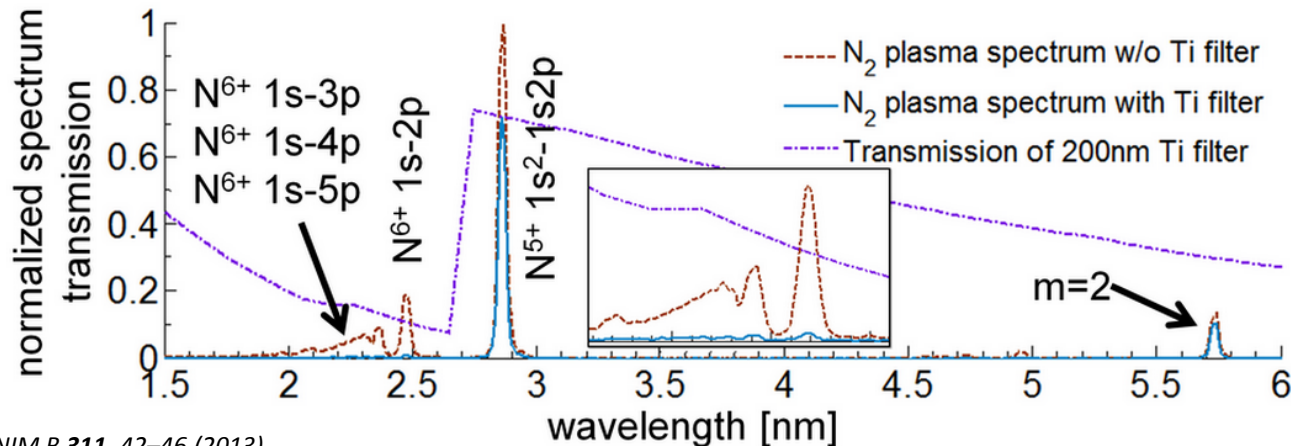


Applied Physics B **111**, 2, 239-247 (2013)

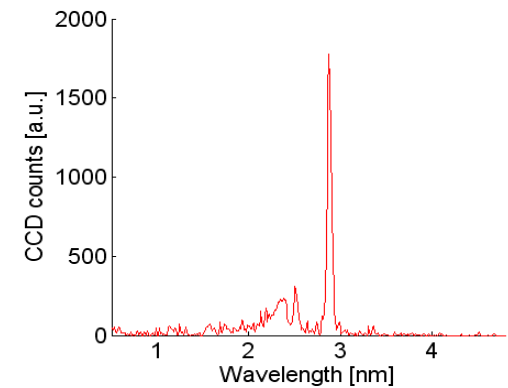


NIM B **268**, 10, 1692-1700 (2010)

Nitrogen emission on the „water window“



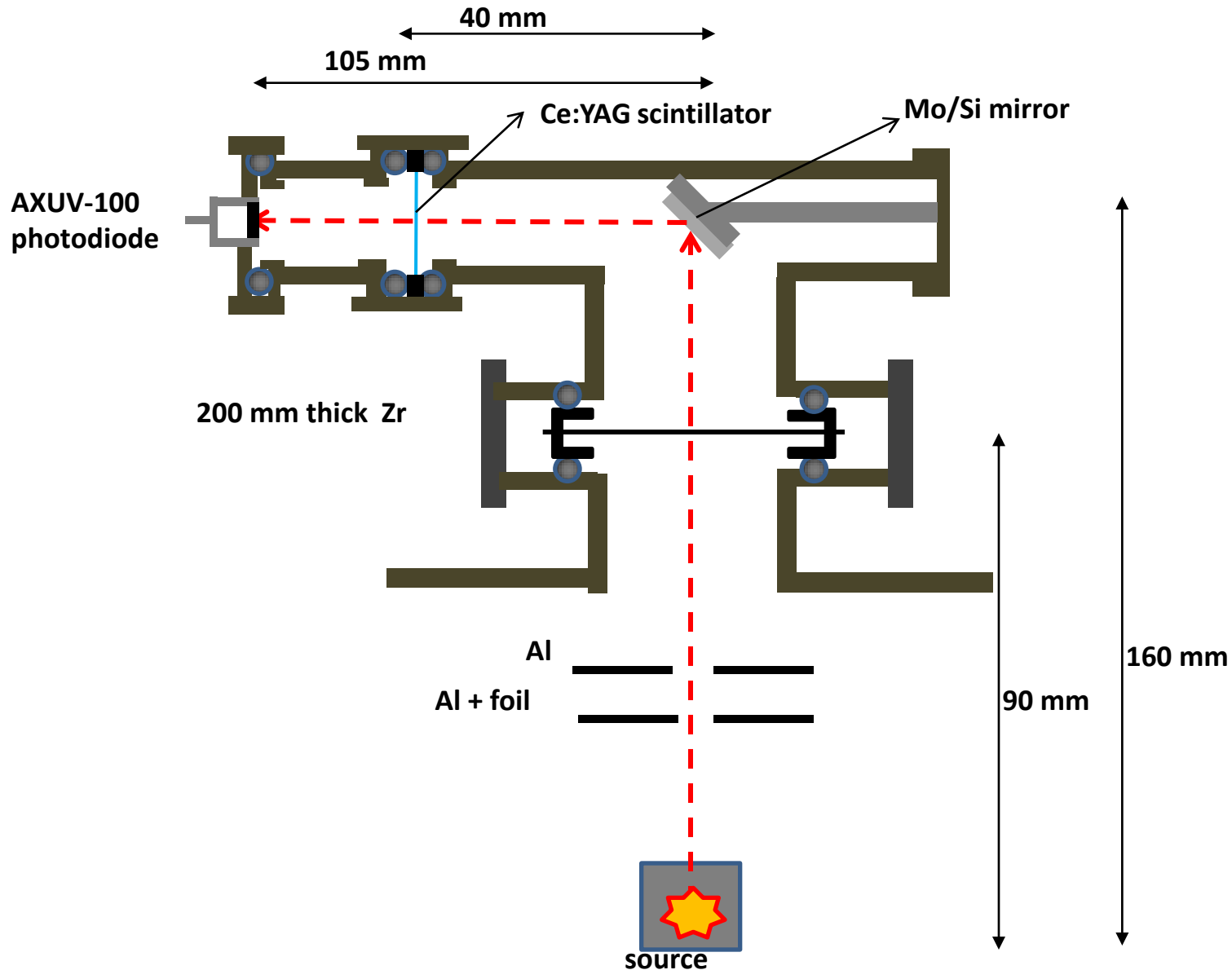
NIM B **311**, 42-46 (2013)



NIM B **268**, 10, 1692-1700 (2010)

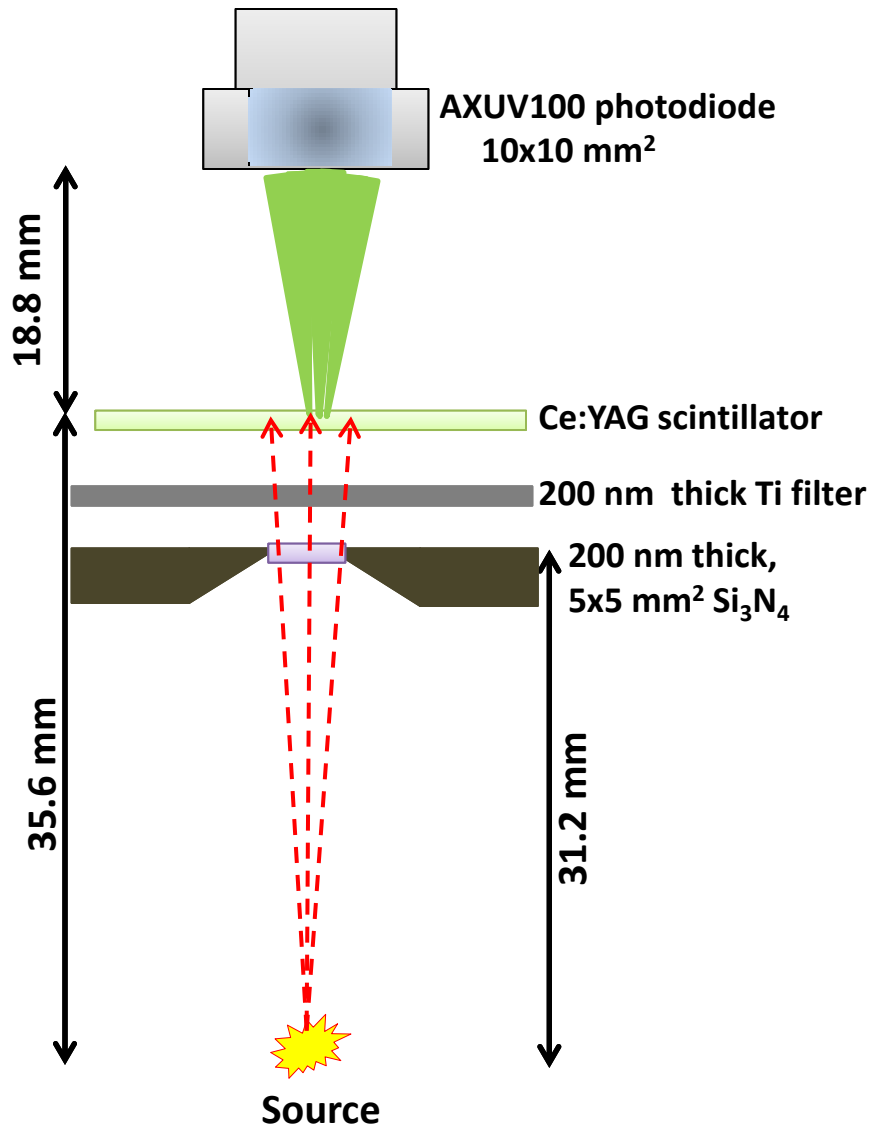
EUV MEASUREMENTS

Schematic diagram of experimental arrangement for the characterization of Ce:YAG scintillator



SXR MEASUREMENTS

Schematic diagram of experimental arrangement for the characterization of Ce:YAG scintillator with SXR



PHOTON FLUX WITH SCINTILATOR

Detectors : AXUV-100 photodiode +
Ce:YAG scintillator
Visible light (Green, $\lambda = 550$ nm), QE = 0.6

Argon

Scintillated light flux = $(1.03 \pm 0.15) \times 10^{10}$
photons/pulse
(dataset: „flux-041-60.csv”)

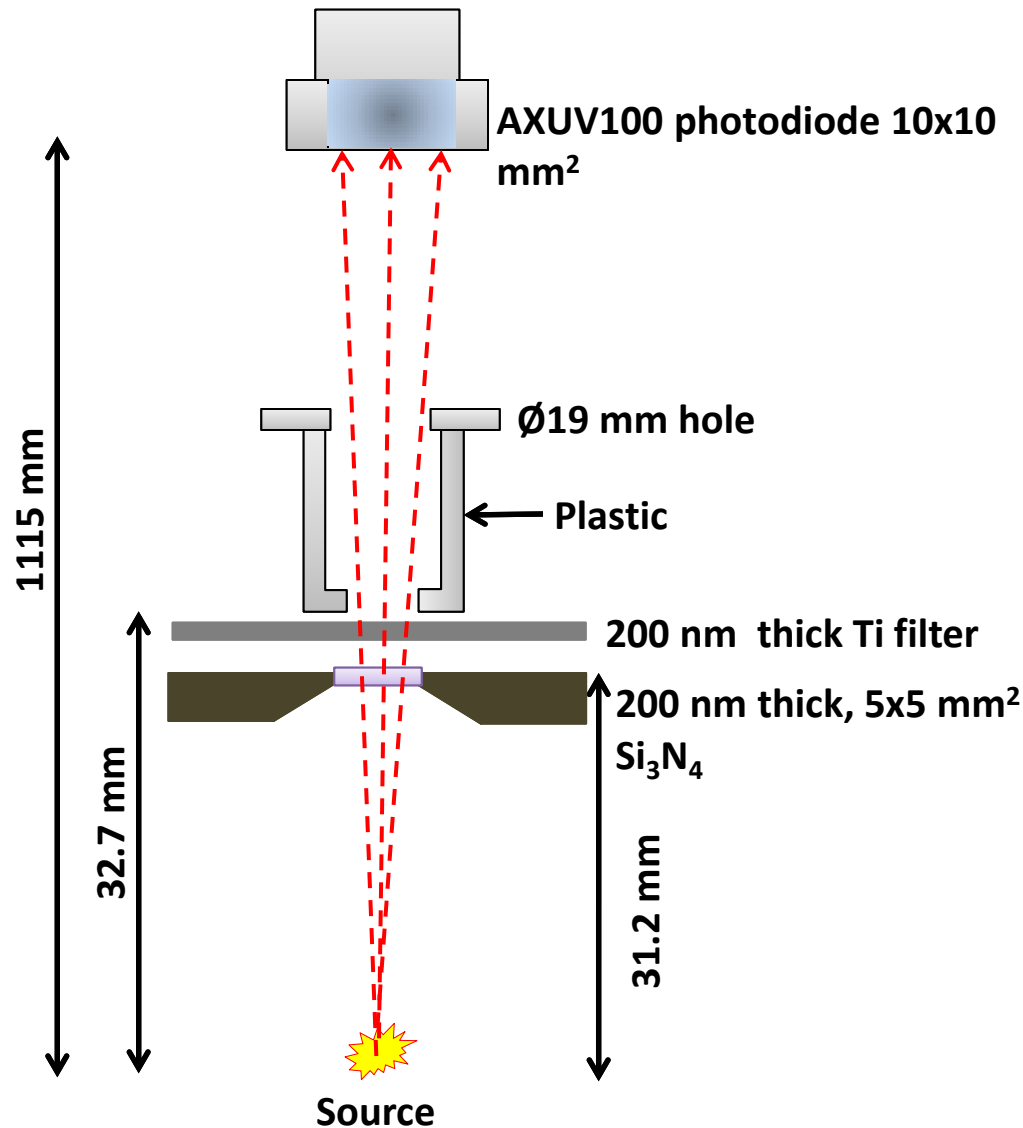
Nitrogen

Scintillated light flux = $(1.86 \pm 0.2) \times 10^8$
photons/pulse
(dataset: „flux-061-80.csv”)

Nd:YAG scattered signal (QE ~ 0.22)

Scintillated light flux = $(1.29 \pm 0.04) \times 10^9$
photons/pulse
(dataset: „flux-081-100.csv”)

Schematic diagram of experimental arrangement for the measurement of SXR photon flux with AXUV-100 photodiode detector without the Ce:YAG scintillator



PHOTON FLUX WITHOUT SCINTILATOR

Detectors : AXUV-100 photodiode
without Ce:YAG scintillator

Argon

Peak $\lambda = 3.19 \text{ nm}$; (bandwidth 2.7-4.5 nm)
QE = 106.83
SXR flux = $(4.64 \pm 0.71) \times 10^8$ photons/pulse
(dataset: „flux-121-140.csv”)

Nitrogen

Peak $\lambda = 2.88 \text{ nm}$; QE = 119.50
SXR flux = $(3.01 \pm 0.34) \times 10^6$ photons/pulse
(dataset: „flux-141-160.csv”)

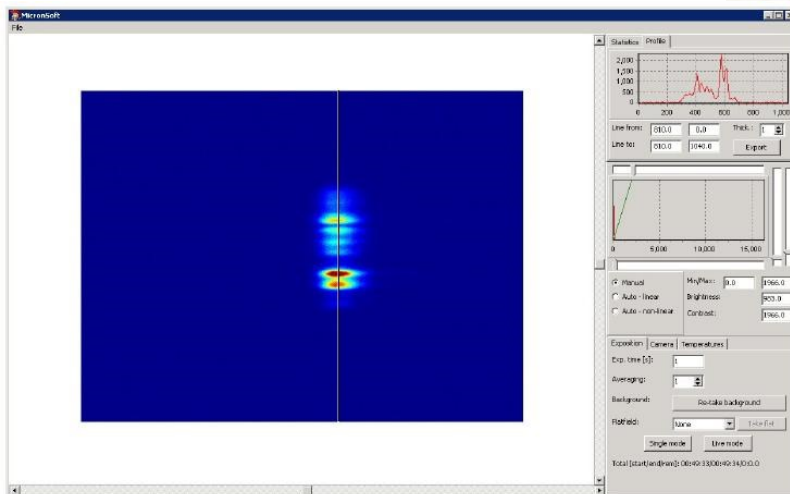
EFFICIENCY CALCULATIONS (photon number)

PARAMETER	Ar data	N ₂ data
SXR flux (photons/pulse) @ 1.1m from source	(4.64±0.71)E+8 QE=106.83	(3.01±0.34)E+06 QE=119.5
SXR flux (photons/pulse) @ Ce:YAG plane (N _{inc})	(1.48±0.23)E+11 QE=106.83	(9.60±1.08)E+8 QE=119.5
Scintillated light flux (N _{sc}) (photons/pulse), QE=0.6	(1.03±0.15)E+10	(1.86±0.2)E+08
Nd:YAG scattered photon flux, QE=0.22	(1.29±0.04)E+9	(1.29±0.04)E+9
Photon efficiency =N _{sc} / N _{inc}	6.9%	19.4%

Xsight™ Micron X-ray CCD Camera

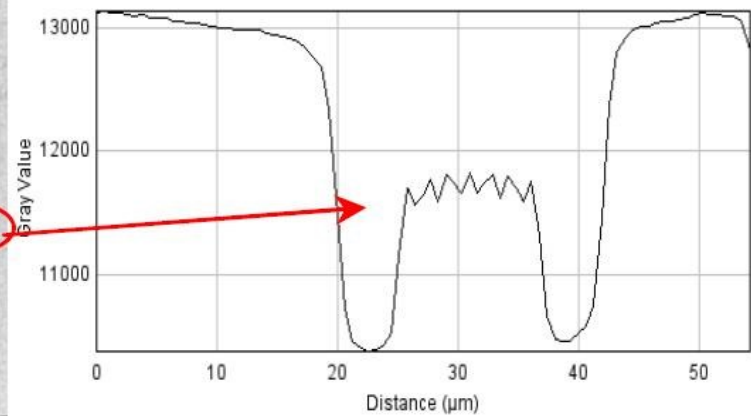
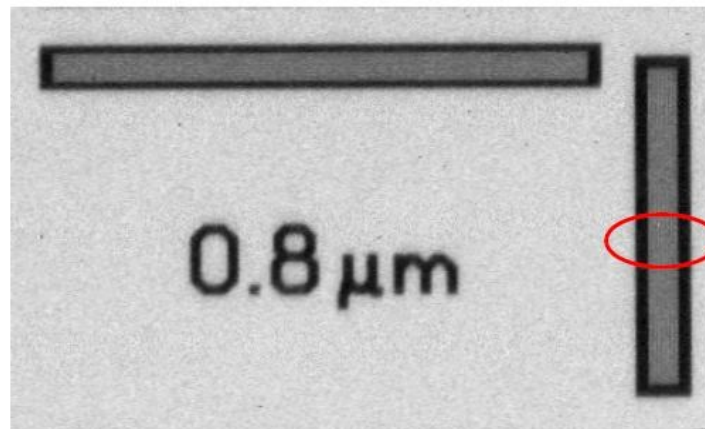
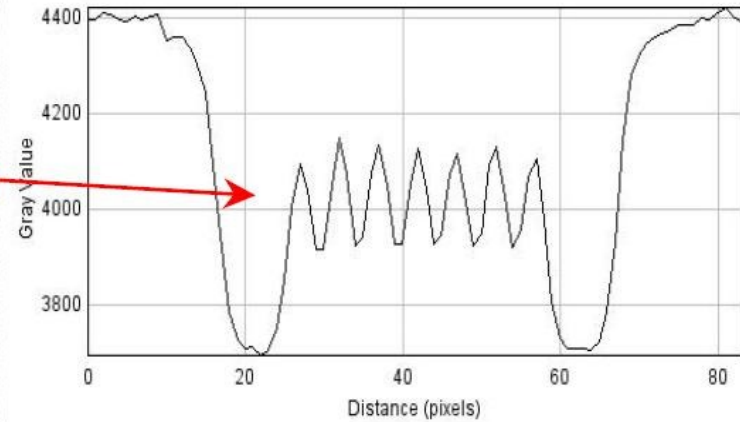
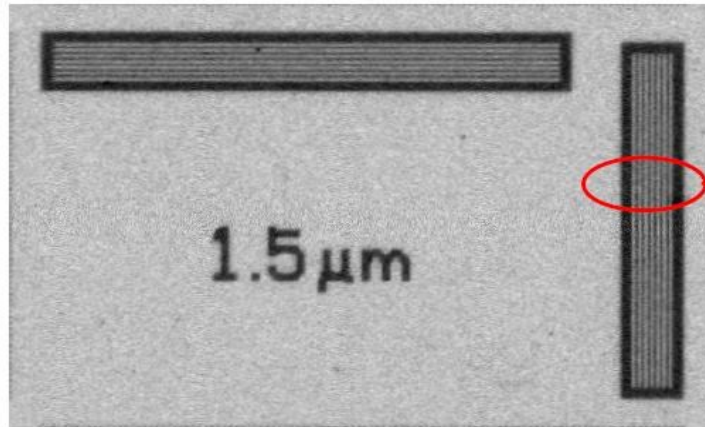
Applications:

- X-ray microscopy
- X-ray microtomography
- X-ray optics adjustment & metrology
- Phase contrast X-ray imaging

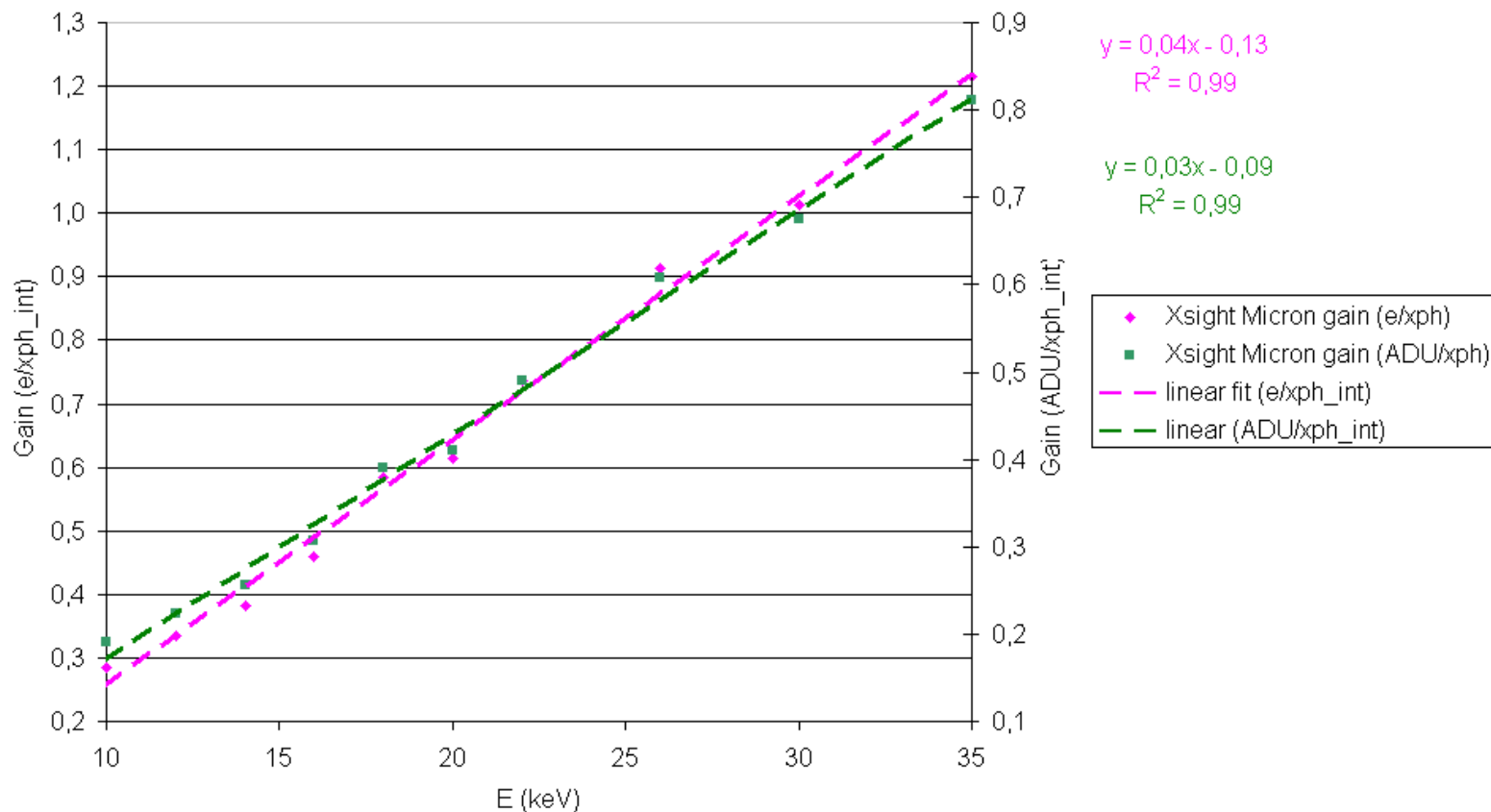


Field of view: 0,90 mm x 0,67 mm
Resolution: $\leq 1 \mu\text{m}$ (@ 8 keV)
Spectral range: 50 eV to 35 keV
Exposure time range: 20 μs to 500 s
Dynamic range: 70 dB
Dimensions: 60 x 70 x 250
Weight: 2.5 kg

XSight™ Micron resolution



Xsight Micron camera - number of electrons / ADU per absorbed photon



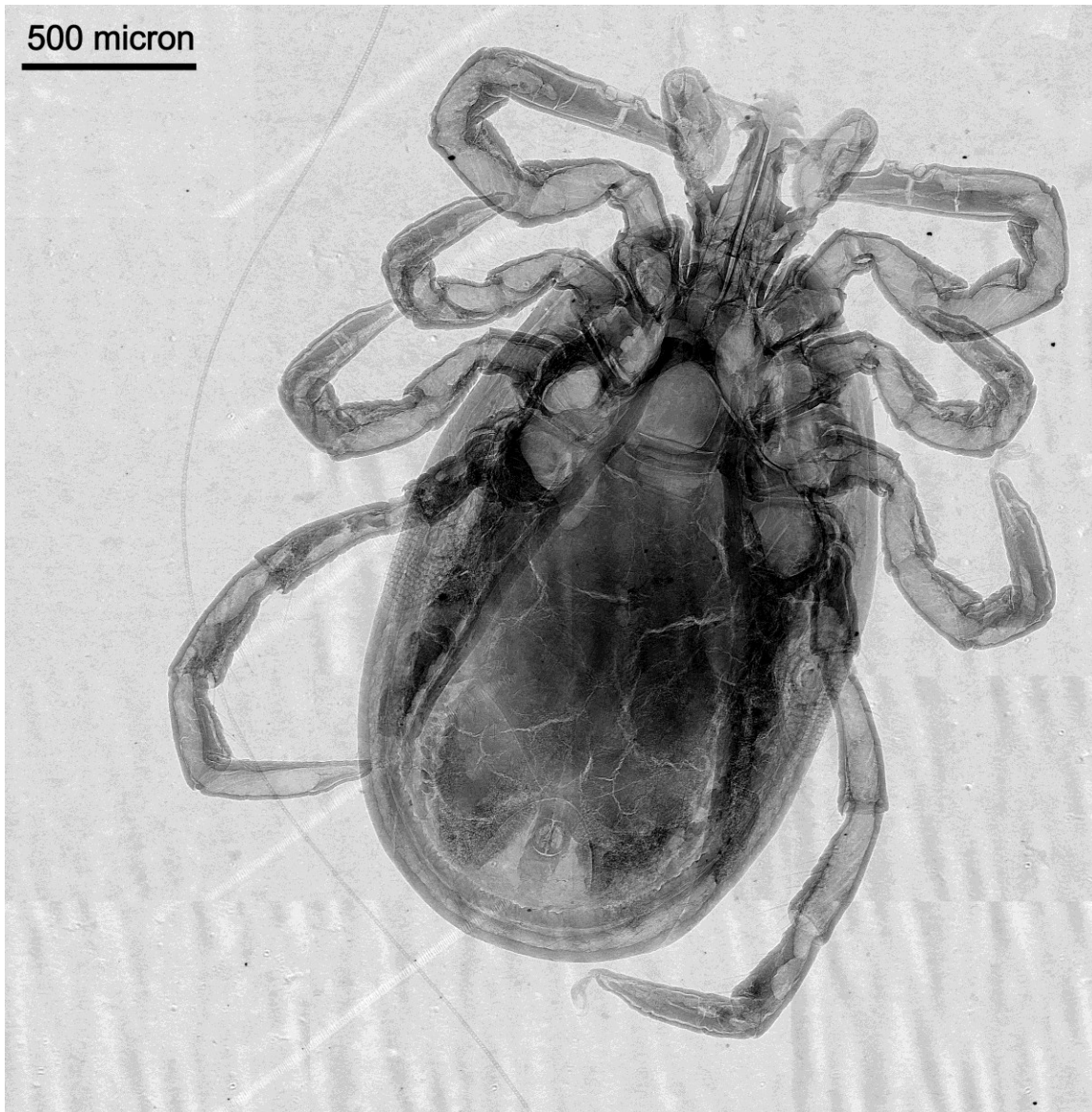
Rigaku XSight Micron camera quantum efficiency in X-ray region

Photon energy (keV)	Detected signal	
	ADU/xph	e/xph
10	0.19	0.28
12	0.22	0.33
14	0.26	0.38
16	0.31	0.46
18	0.39	0.59
20	0.41	0.61
22	0.49	0.74
26	0.61	0.91
30	0.68	1.01
35	0.81	1.22

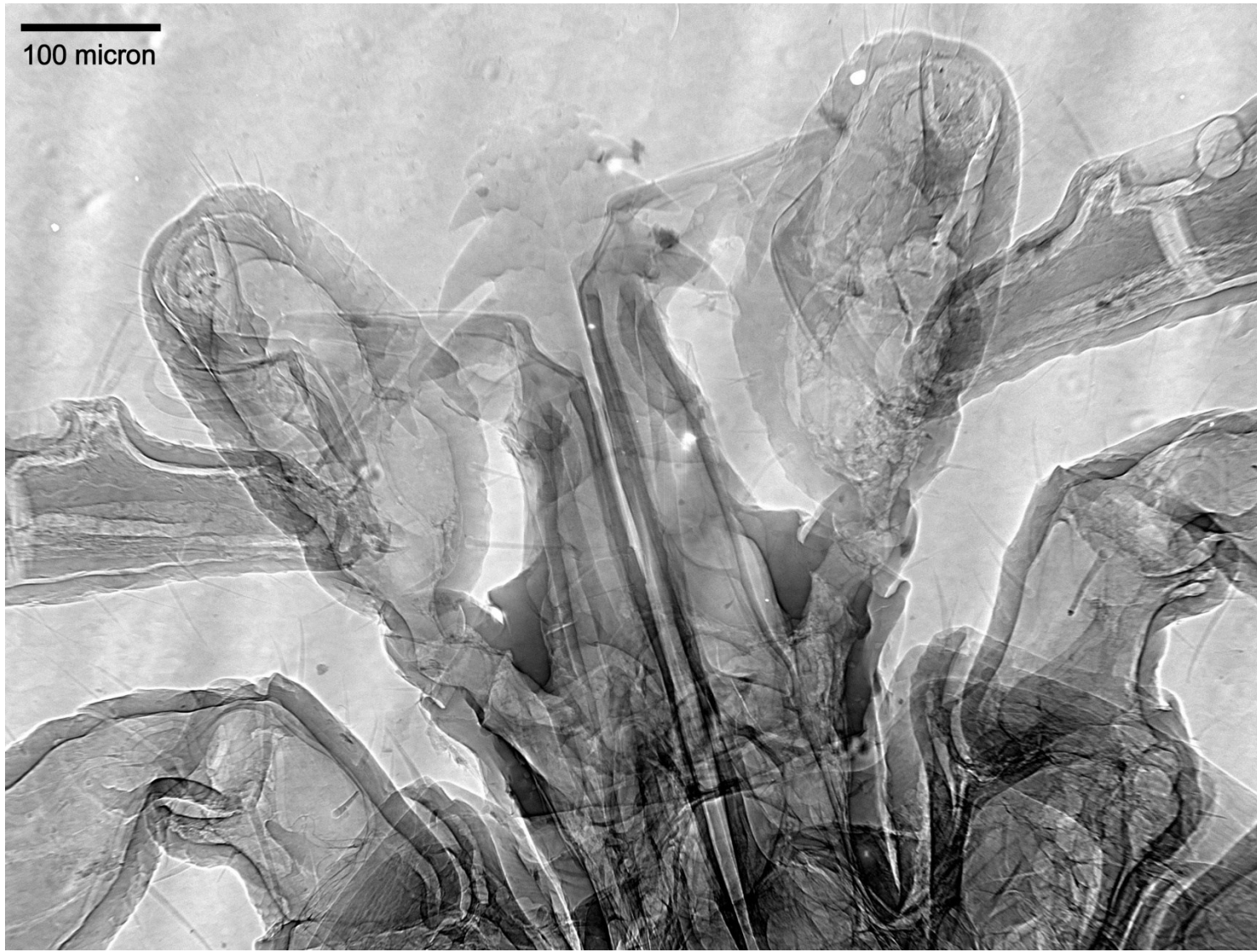
The Xsight Micron camera quantum efficiency

Applications

- EUV / SXR lithography
- EUV / SXR radiography
- EUV / SXR high contrast imaging
- EUV / SXR optics metrology
- EUV / SXR optics alignment



X-ray image of Ixodes Ricinus
(Taken by XSight Micron at RITE laboratory
using 80 W microfocus X-ray tube with Cu
target)



X-ray image of Ixodes Ricinus

(Taken by XSight Micron at RITE laboratory using 80 W microfocus X-ray tube with Cu target)

Rigaku nano3DX

High Resolution 3D X-ray Microscopy

POWER : Ultra High flux, up to 1200 W

ENERGY: Cr, Cu , Mo

DETECTOR: 3300 x 3300 x 2500 Matrix

OPTICS: No projection magnification

EASY: Minimal Alignment or optimisation



Rigaku nano3DX



RES	CFRP
FOV:	0.27um voxel
ENERGY:	3200 x 3200 x 2500 (0.9mm)
	Cu Anode 8keV

Summary

- **Quantum efficiency of selected monocrystal scintillators was measured in EUV, SXR and XR radiation ranges**
- **Submicron resolution EUV/BEUV/SXR/XR imaging detectors were characterized**
- **Selected applications of submicron resolution EUV/BEUV/SXR/XR imaging detectors in microscopy and tomography were shown**

THANK YOU FOR ATTENTION



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